# Low-temperature electrical conductivity of Ta-compensated sodium bronze near the metal-insulator transition

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We report the results of electrical conductivity  $[\sigma(T)]$  measurements in the temperature range 300 > T > 0.1 K on single crystals of tantalum-substituted sodium tungsten bronze  $(Na_x Ta_y W_{1-y} O_3)$  with compositions near the metal-insulator transition  $(x - y \approx 0.19)$ . We find that over the entire temperature range investigated, strong interaction effects dominate the temperature dependences of  $\sigma(T)$ . For samples that lie on the metallic side, the  $\sigma(T)$  values in the temperature range 4 > T > 0.3 K follow a power law in T with an exponent  $\frac{1}{3}$  and  $\sigma(T=0)\approx 0.01\sigma_{Mott}$ . This arises due to interaction effects in the critical regime, where the coherence length is very large due to the proximity to the metal-insulator transition. These samples below 0.3 K show signatures of a weak superconducting transition. The  $\sigma(T)$  of the insulating samples below 4 K either show correlated hopping behavior or follow a power law with  $\sigma(T=0)=0$ . At higher temperatures (T > 10 K), the  $\sigma(T)$  of both types of samples show an almost linear dependence with T, which we suggest as arising from electron-phonon interactions.

## I. INTRODUCTION

Composition-driven metal-insulator (M-I) transitions in cubic perovskite oxides have been extensively studied in the past.<sup>1</sup> In these oxides, when the conductivity  $(\sigma)$ reaches the Mott value  $\sigma_{\text{Mott}} (\approx e^2 k_F / 3\pi^2 \hbar$ , where  $k_F$  is the Fermi wave vector), the temperature coefficient of conductivity  $(d\sigma/dT)$  changes sign from  $d\sigma/dT < 0$  for  $\sigma > \sigma_{\rm Mott}$  to  $d\sigma/dT > 0$  for  $\sigma < \sigma_{\rm Mott}$ . In the past the change in sign of  $d\sigma/dT$  had been taken as the signature of the *M*-*I* transition. With the advent of scaling theory,<sup>2</sup> it was shown that  $d\sigma/dT > 0$  does not necessarily imply loss of metallicity [i.e.,  $\sigma(T=0)\neq 0$ ]. However, only in very few cases have the concepts evolving out of scaling theories been applied to this class of materials.<sup>3-6</sup> This is because of the lack of experimental investigations in them for T < 10 K. In order to look for the quantum corrections to  $\sigma$  near the *M*-*I* transition it is necessary to do these measurements at much lower temperatures (T < 4)K). In this investigation we have carried out a precise measurement of  $\sigma$  in the temperature range 300 > T > 0.1K to explore the exact nature of  $\sigma(T)$  at low temperatures when we are close to the M-I transition.

We have chosen Ta-substituted  $Na_x WO_3$  for this investigation. Our choice is dictated by two reasons: (i) the availability of well-characterized single crystals with composition close to the *M-I* transition and (ii) the existence of extensive investigations on the *M-I* transition in this system.<sup>3,7</sup>

The rest of the paper is divided into four sections. In Sec. II we have given a brief summary of the past work on this system that is relevant to the present investigation. The details of the experiment and results are given in Secs. III and IV. In Sec. V we have presented the analysis of our results and discussions.

# II. *M-I* TRANSITION IN $Na_x WO_3$ AND $Na_x Ta_y W_{1-y}O_3$

Na<sub>x</sub>WO<sub>3</sub> can be obtained as a cubic system for x > 0.4. For x < 0.4 one obtains a tetragonal phase as the roomtemperature equilibrium phase.<sup>8</sup> Cubic phases with  $x \approx 0.22$  were made by out-diffusion of Na from systems with x > 0.4.<sup>9</sup> It was shown that the cubic phase could also be stabilized by Ta substitution so that the resulting compound had the general formula Na<sub>x</sub>Ta<sub>y</sub>W<sub>1-y</sub>O<sub>3</sub>, where  $y \approx 0.2$ .<sup>10</sup> The empty 5d orbital of Ta compensates for the excess carriers coming from Na and can make (x - y) < 0.2 while retaining the cubic structure. The substitution, however, increases the disorder. Thus one can approach the *M-I* transition without interference coming from crystallographic changes. The *M-I* transition occurs at  $(x-y) \approx 0.19$ .<sup>3</sup>

WO<sub>3</sub>, which is an insulator, has corner-sharing WO<sub>6</sub> units and a direct band gap of 3.5 eV. The Na goes into the interstitial and contributes one electron to the empty  $\pi^*$  band formed by hybridized W 5d and O 2p orbitals. The electrical conduction arises due to the impurity band (like Si:P). The *M-I* transition is believed to occur in this impurity band and is of the Anderson type.<sup>7</sup> We will show that the *M-I* transition is also strongly affected by interaction effects.

In Fig. 1 we have presented the electrical conductivity  $(\sigma)$  as a function of the temperature (T) for a number of different compositions. In Fig. 2 we have shown the room-temperature conductivity  $\sigma_{295 \text{ K}}$  as a function of the charge carrier concentration (x for Na<sub>x</sub>WO<sub>3</sub> and x-y for the Ta-substituted case). The data have been obtained from a number of sources.<sup>3,7</sup> The following important features may be noted from Figs. 1 and 2. (i) The change in sign of  $d\sigma/dT$  occurs at around  $x \approx 0.3$  or  $x-y \approx 0.35$  when the  $\sigma_{295 \text{ K}} \approx \sigma_{\text{Mott}} \approx 2.5 \times 10^2 \text{ S/cm}$ . (ii) Ta substitu-

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FIG. 1. Electrical conductivities of  $Na_x Ta_y W_{1-y}O_3$  system for different values of x and y near the metal-insulator transition. The data have been obtained from Refs. 3, 7, and 9. For A, x=0.63, y=0.0; B, x=0.61, y=0.17; C, x=0.30, y=0.0; D, x=0.22, y=0.0; E, x=0.45, y=0.16; F, x=0.34, y=0.10; G, x=0.35, y=0.16; H, x=0.34, y=0.16.

tion introduces disorder so that for the same effective carrier concentration  $\sigma$  is lower. (iii) The system is metallic down to  $(x-y)\approx 0.19$  with  $\sigma_{1 \text{ K}} \ll \sigma_{\text{Mott}}$ .

It is truly fascinating that in these systems there exist metallic states with  $\sigma \ll \sigma_{Mott}$ . The samples we studied have their carrier concentrations very close to the critical concentration for the *M-I* transition and even in the metallic state the room-temperature conductivity  $\sigma_{295 \text{ K}}$  is much smaller than  $\sigma_{Mott}$ .

#### **III. EXPERIMENT**

The single crystals of  $Na_x Ta_y W_{1-y}O_3$  are of nominal composition (x = 0.35, y = 0.16) and (x = 0.34, y = 0.16). These crystals belong to the same batch as those used in earlier studies.<sup>3</sup> The samples marked M in Table I are metallic and those marked I are insulating.

Typical crystals were 1-2 mm on the sides and around 0.3 mm thick. We used a van der Pauw method<sup>11</sup> to measure the resistivity. The crystals were mounted on a mi-



FIG. 2. Room-temperature conductivities of  $Na_xWO_3$  and  $Na_xTa_yW_{1-y}O_3$  as a function of x or x - y (effective carrier concentration). The effect of disorder on  $\sigma$  due to Ta substitution can be seen.

croscope cover glass with a small amount of GE varnish. On each crystal, four small contact pads were made in the van der Pauw configuration by evaporating Cr (200 Å) followed by Au (1000 Å). The electrical contacts to these pads were also made by evaporating Cr/Au films. This method allowed us to run four samples at a time on one single cover glass. The cover glass was mounted on cold fingers of the cryostats with a little Apieozon N grease. The resistance measurements were made by a low-frequency ( $\approx 22$  Hz) ac method using a lockin amplifier and a balancing arm with a standard resistor. Depending on the sample resistance and the measuring temperature the measuring current was varied between 0.3 and 100  $\mu$ A.

In the insulating samples the self-heating prevented us from going below 0.4 K. In the metallic samples data were taken down to 0.1 K. The accuracy of the absolute value of  $\sigma$  was around  $\pm 15\%$  because of the finite size of

				Temperature dependence of $\sigma$			
	Na <sub>x</sub> Ta <sub>y</sub> V	$V_{1-\nu}O_3$		-	300 > T > 10  K $\sigma(T) = \sigma_h(0) + \sigma_{1h} T^{\alpha}$		
Nominal	Sample	$\sigma_{295 \text{ K}}$	$\sigma_{0.5 \ \mathrm{K}}$	4 > T > 0.3 K			
composition	code	S/cm	S/cm	$\sigma(T) =$	$\sigma_h(0)$	$\sigma_{1h}$	α
Metal	<b>M</b> 1	88.2	6.6	$3.1+4.4T^{1/3}$	11.7	0.24	1.00±0.03
x = 0.35	M2	157.2	12.5	$6.4 + 7.7T^{1/3}$	19.7	0.64	0.94±0.02
y = 0.16	<b>M</b> 3	133.4	9.2	$4.0+6.5T^{1/3}$	15.5	0.50	0.95±0.02
Insulator	<i>I</i> 1	6.0	$1.16 \times 10^{-3}$	$3.39 \times 10^{-3} T^{1.55}$	0.08	3.6×10 <sup>-3</sup>	1.29±0.02
x = 0.34	13	64.1	$4.66 \times 10^{-2}$	$1.1 \times 10^{-1} T^{1.24}$	1.03	$6.8 \times 10^{-2}$	1.20±0.02
<i>y</i> =0.16	<i>I</i> 2	6.0	$7.65 \times 10^{-4}$	$0.8 \times \exp\left[-\left[\frac{50}{T}\right]\right]$	0.10	$5.1 \times 10^{-3}$	1.23±0.02

TABLE I. Electrical conductivities and the fit parameters of  $\sigma(T)$  in various temperature ranges. *M* denotes metallic  $[\sigma(T=0)\neq 0]$  and *I* denotes insulating  $[\sigma(T=0)=0]$  samples.

the contacts and also the somewhat irregular sample shape. The precision in the resistance measurement was better than 0.1%.

#### **IV. RESULTS**

Typical representative  $\sigma(T)$  for one metallic and one insulating sample are shown in Fig. 3 for 300 > T > 0.4K. The data show that for T > 10 K,  $\sigma(T)$  of both types of samples vary almost linearly with T. (This was also observed in Ref. 3.) But for T < 10 K,  $\sigma(T)$  of the Mtype sample (x = 0.35, y = 0.16) almost saturates at some residual value, showing the existence of a finite  $\sigma(T=0)$ . On the contrary,  $\sigma(T)$  of the other sample curves to lower values as T is decreased, showing the absence of a finite zero-temperature conductivity.

At higher temperature (T > 10 K),  $\sigma(T)$  of all the samples follow a power-law relation,

$$\sigma(T) = \sigma_h(0) + \sigma_{1h} T^{\alpha} , \qquad (1$$

 $\alpha$  for the metallic samples being around 1 and those for the insulating samples around 1.2-1.3 (see Table I). One can see that, even for the insulating samples, if we extrapolate the conductivity  $\sigma$  to T=0 from measurements done down to 10 K we find a nonzero  $\sigma$  [i.e.,  $\sigma_h(0)\neq 0$  in Eq. (1)]. This shows that it is dangerous to talk about  $\sigma(T=0)$  from measurements done down to 10 K only. In fact, when we are so close to the *M-I* transition it is difficult to distinguish a metal from an insulator by hightemperature measurements alone. Similar hightemperature power-law behavior [Eq. (1)] with  $\alpha \approx 1-1.3$ has been seen in metallic glasses and also in another disordered oxide  $In_x O_y$ .<sup>4,12</sup>

Below 4 K (4>T>0.3 K),  $\sigma(T)$  of the metallic samples were found to follow a relation of the type

$$\sigma(T) = \sigma(0) + \sigma_1(T) = \sigma(0) + \sigma_1 T^{1/3} , \qquad (2)$$

with  $\sigma(0) \approx 3-6$  S/cm (see Fig. 4). This is the extrapolat-



FIG. 3. Temperature dependence of the conductivity for a metallic  $(\bigcirc)$  and an insulating sample  $(\times)$ . The data for only two representative samples are shown for clarity.



FIG. 4. Low-temperature  $T^{1/3}$  behavior of the conductivity for the metallic samples.

ed zero-temperature conductivity for the metallic samples and, as can be seen,  $\sigma(0)/\sigma_{Mott} \approx 0.01$ . This may be one of the lowest zero-temperature conductivities recorded for a metallic sample.

For the insulating samples,  $\sigma(T)$  below 4 K follow either a power law,  $\sigma(T) \approx \sigma_0 T^n$  with n > 1 or a hopping relation of the type

$$\sigma(T) = \sigma_0 \exp[-(T_0/T)^n], \qquad (3)$$

with  $n \approx 0.42$  and  $T_0 \approx 50$  K. This has been shown in Fig. 5, which is a log  $\sigma vs (1/T)^{1/2}$  plot. The sample with the lowest  $\sigma$  [which follows Eq. (3)] shows a limiting linear region in this plot for T < 4 K. For the other insulating sample, which has a higher  $\sigma$ , even at 0.4 K we do



FIG. 5. Low-temperature hopping conductivity of the insulating samples. For one sample (lower  $\sigma$ ) the onset of correlated hopping can be seen for T < 4 K as a limiting linear region in the log $\sigma$  vs  $1/T^{1/2}$  plot. For the other sample (higher  $\sigma$ ) the limiting linear region does not develop even down to 0.4 K.



FIG. 6. Anomalous drop in the resistance observed in metallic samples for T < 0.3 K.

not find a limiting linear region in the  $\log \sigma$  vs  $(1/T)^{1/2}$  plot (Fig. 5). This implies that for this sample the hopping region [following Eq. (3)] will start at even lower temperatures.

For the metallic samples below 0.3 K we find a new feature. This is shown as a resistance (R) vs T plot in Fig. 6. It can be seen that at T < 0.3 K the resistance falls again. This feature is present in all the metallic samples that we studied, though the exact temperature where Rstarts to fall and the extent of the change depend on the sample. We have checked that this is no spurious effectarising due to local heating by measuring the resistance, with the measurement power varying by at least three orders in magnitude. We cannot suggest anything definite about this fall. But we point out that the fall in resistance looks rather similar to that observed in bulk disordered superconductors.<sup>13</sup> From this similarity we suggest that this fall in the resistance at lower temperature may be a weak superconducting transition that is severely broadened by the disorder. Discussion of this feature is beyond the scope of this paper and for this reason we have used the data down to 0.3 K only for the purpose of fitting to Eq. (2).

Before we end this section we point out one more important observation. Even for the same nominal composition, the  $\sigma_{295 \text{ K}}$  for the metallic samples can vary by a factor of 2, and those for the insulating samples can vary by a factor of 10. Near the *M-I* transition the  $\sigma$  is a strong function of the composition. As a result, a little composition fluctuation or a little uncertainty in the composition can change the  $\sigma$  of samples with the same nominal composition.

#### **V. DISCUSSION**

In this section we will try to analyze the observations of the preceding section and will show that the temperature dependences of  $\sigma$  of these oxides are dominated by interaction effects in the complete temperature range investigated.

## A. Metallic samples (Na<sub>0,35</sub>Ta<sub>0,16</sub>W<sub>0,84</sub>O<sub>3</sub>) below 4 K

We suggest that for the metallic samples the power-law behavior of  $\sigma(T)$  [Eq. (2)] arises from interaction effects. In disordered solids with strong electron-electron interactions,  $\sigma$  at low temperatures (T < 2 K) follow a power law  $T^{1/2}$ . This has been seen in a number of materials.<sup>5,14,15</sup>

The  $T^{1/3}$  dependence of  $\sigma$  that we have seen [see Eq. (2) and Fig. 4] can also come from interaction effects if we are in the critical regime  $l_{\text{int}} < \xi$ , where  $l_{\text{int}}$  is the inelastic scattering length and  $\xi$  is the coherence length.<sup>14,16</sup>

For weakly disordered systems one can get the regime  $l_{\rm int} > \xi$  at moderately low temperatures. In these systems the quantum correction  $\sigma_1(T) ~(\approx e^2/\hbar l_{\rm int})$  is smaller than the zero-temperature conductivity  $\sigma(0) ~(\approx e^2/\hbar\xi)$  and the corrections due to electron-electron interactions give the  $T^{1/2}$  term in the conductivity.<sup>14,15</sup>

When we are very close to the *M-I* transition (as in our case)  $\xi$  can become very large, and even at low temperatures such as ours we can have  $\xi > l_{int}$ . In such cases the correction term ( $\sigma_1$ ) can be of the same order or even larger than  $\sigma(0)$ , and it has been shown that the electron diffusivity *D* and  $l_{int}$  are related by the relation<sup>14,16</sup>

$$l_{\rm int} \approx (\xi D \tau_{\rm int})^{1/3} , \qquad (4)$$

where  $\tau_{int}$  is the inelastic scattering time. This can be contrasted to the more common relation

$$l_{\rm int} \approx (D\tau_{\rm int})^{1/2} , \qquad (5)$$

which is valid in the regime  $l_{\text{int}} > \xi$ .

In strongly localized and interacting systems, the dominant scattering time is the thermal time constant itself, given as  $^{14}$ 

$$\tau_{\rm int} = \hbar / k_B T \ . \tag{6}$$

It can then be seen from Eqs. (4) and (6) that in the critical regime the correction term  $\sigma_1(T) \propto l_{\rm int}^{-1} \propto T^{1/3}$ . The magnitude of the correction can be estimated as<sup>14,17</sup>

$$\sigma_1(T) \approx (e^2 / \hbar) G_c^{2/3} [g(E_F) k_B]^{1/3} T^{1/3} , \qquad (7)$$

where  $G_c \approx (2/3\pi^3)$ , and  $g(E_F)$  is the density of states at the Fermi level  $E_F$ . The numerical factor  $G_c$  depends on the detailed nature of the scaling theory used for calculations and is an approximation.<sup>17</sup> Using  $g(E_F) \approx 5 \times 10^{33}$  $\mathrm{erg}^{-1}\mathrm{cm}^{-3}$  as obtained from the specific heat,<sup>18</sup> we obtain from Eq. (7)  $\sigma_1 \approx 15$  S/cm K<sup>1/3</sup>. This is close to  $\sigma_1 \approx 5-8$ S/cm K<sup>1/3</sup> obtained from experiment (see Table I). The difference of a factor of 2 or 3 between the calculated and the experimental values may come from the numerical factor  $G_c$  used in Eq. (7). Also the  $g(E_F)$  used was the same for Na<sub>0.23</sub>WO<sub>3</sub>. It is quite possible that the  $g(E_F)$ of our samples with  $x - y \approx 0.19$  will be somewhat lower. [The  $g(E_F)$  may be strongly dependent on the concentration as the *M-I* transition is approached, as has been seen in Si:P.<sup>19</sup>

From the  $\sigma(0)$  term, using  $\sigma(0) \approx 2/3(e^2/\hbar\xi)$ , we estimate  $\xi \approx 2000-5000$  Å. From the Einstein relation,  $\sigma = e^2g(E_F)D$ , we find  $D \approx 1.7 \times 10^{-2}$  cm<sup>2</sup>/s at 0.5 K. From Eq. (4) we estimate  $l_{int} \approx 100-200$  Å at 0.5 K. We

can thus justify that even down to low temperatures the inequality  $l_{\rm int} < \xi$  holds. (Since  $l_{\rm int}$  decreases with increasing temperature, if the inequality is valid at the lowest temperature it will also hold at higher temperatures.)

We conclude that in the metallic samples the temperature dependence of  $\sigma$  for T < 4 K arises due to strong interaction effects. At low temperatures the interaction effects are so strong that the only relevant time scale is the thermal time constant given by Eq. (6). Also, it may be noted that for these samples the  $\sigma(T=0) \approx 0.01 \sigma_{Mott}$ .

#### B. Insulating samples (Na<sub>0.34</sub>Ta<sub>0.16</sub>W<sub>0.84</sub>O<sub>3</sub>) below 4 K

At low temperatures in the insulating side of the *M-I* transition one expects the conduction to take place by hopping, with  $\sigma(T)$  given by Eq. (3). For the Mott-type variable range hopping,  $n = \frac{1}{4}$  and the energy scale  $T_0$  is given by  $k_B T_0 \approx 1/[g(E_F)\xi^3]$ .<sup>21</sup> (In the insulating side,  $\xi$  is the localization length, which diverges at the *M-I* transition.) In the presence of electron correlation this is modified. In the case of correlated hopping,  $n = \frac{1}{2}$  and the energy scale  $T_0$  is given by<sup>22</sup>

$$k_B T_0 \approx 2.8 (e^2 / \kappa \xi) , \qquad (8)$$

where  $\kappa$  is the static dielectric constant.

The hopping relation [Eq. (3)] generally holds for  $T \ll T_0$ . Since we are close to the *M*-*I* transition,  $\xi$  will be large in our samples and  $T_0$  will be low. This reflected in the low-temperature (T < 4 K) behavior of  $\sigma$ . We find that the  $\sigma(T)$  of the insulating sample with the lowest  $\sigma$  value follows Eq. (3), with  $n \approx 0.42$  and  $T_0 \approx 50$  K. Since *n* is closer to  $\frac{1}{2}$  we conclude that the hopping in this case is controlled by correlation effects. This is expected, because in the metallic side we did find evidence of rather strong interactions. For this sample, from  $T_0$  using Eq. (8) we obtain  $\xi \approx 1500$  Å. This is a reasonable value, given the closeness to the *M*-*I* transition. (For the metallic samples we estimated  $\xi \approx 1000-2000$  Å.)

For the other two insulating samples, which have higher  $\sigma$ , the localization length  $\xi$  will be even higher and  $T_0$  will be lower. As a result, the hopping behavior obeying Eq. (3) will be seen at lower temperatures. It can be seen in Fig. 6 that for these samples the limiting lowtemperature linear region has not been observed in the log $\sigma$  vs  $1/T^{1/2}$  plot for T > 0.4 K. It is likely that the limiting linear region will show up at even lower temperatures. Our observation is therefore consistent with the fact that these samples are very close to the *M-I* transition and the localization lengths are rather large. The low-temperature  $\sigma$  (T < 4 K) for these samples can be fitted to a power law of the type  $\sigma \approx \sigma_0 T^n$ , with  $n \approx 1.2-1.5$ . It should be pointed out that over a limited temperature range it is difficult to distinguish if  $\sigma(T)$  follows Eq. (3) or the power law with n > 1.

We conclude this section by noting that the lowtemperature  $\sigma$  of the insulating samples are governed by correlated hopping. This will then suggest that a Coulomb gap opens up in the single-particle density of states at  $E_F$ .<sup>22</sup>

#### C. High-temperature behavior (T > 10 K)

For both metallic and insulating samples we find that for T > 10 K,  $\sigma$  follow Eq. (1). The only difference is that the  $\sigma_h(0)$  for the metallic samples are higher than those of the insulating samples (see Table I). Also, the exponent  $\alpha \approx 1$  for the metallic samples and  $\alpha \approx 1.2-1.3$  for the insulating samples. In Fig. 7 we have plotted  $\alpha$  and  $\sigma_h(0)$  for all the samples as a function of  $\sigma_{295 \text{ K}}$ , which may be treated as a measure of the disorder. We find that both  $\alpha$  and  $\sigma_h(0)$  vary systematically with  $\sigma_{295 \text{ K}}$ , although there is a relative rapid change occurring around the *M-I* transition. We will show that it is likely that the high-temperature behavior of  $\sigma$  in both the materials is a manifestation of the electron-phonon interactions.

In the critical region  $(l_{int} < \xi)$  the conduction starts to become macroscopic in the length scale comparable to  $l_{int}$ . In this situation a measurement done in the scale  $l_{int}$ cannot distinguish between a metal and an insulator.<sup>16</sup> In this case the macroscopic conductivity is given by

$$\sigma \approx e^2 / \hbar l_{\rm int} \tag{9}$$

and  $\sigma \gg \sigma(0)$ . It has been argued that in this case the result will be the same for both the localized states and the extended states.<sup>16</sup> This implies that close to the *M-I* transition, when  $\xi$  is large and the temperature is such that  $T \ge T_0$ , the temperature dependence of  $\sigma$  will be governed by the temperature dependence of  $l_{\text{int}}$  [see Eq. (9)].

In general,  $\tau_{int} \propto T^{-p}$ . From Eqs. (4) and (9) we find that  $\sigma \propto \tau_{int}^{-1/3} \propto T^{p/3}$ . We can then identify  $\alpha$  of Eq. (1) with p/3. At high temperatures  $\tau_{int}$  is determined by the electron-phonon interactions and  $p \approx 2-4$ .<sup>20</sup> In that case  $\alpha \approx \frac{2}{3} - \frac{4}{3}$ . The  $\alpha$  determined by us from the experiment (see Table I) also lies within this range. The exact value of p depends on the phonon polarization and also on the relative magnitudes of the phonon wavelength  $\lambda$  and the elastic mean free path of the electron  $l_{\rm el}$ . In our case the ratio  $l_{\rm el}/\lambda$  is typically less than 1. As the ratio becomes smaller, the exponent p generally increases.<sup>20</sup> In our case



FIG. 7. Dependence of the high-temperature power-law fit parameters (see Table I) on the room-temperature conductivity  $\sigma_{295 \text{ K}}$ .

we also find that as  $\sigma_{295 \text{ K}}$  decreases (i.e.,  $l_{el}$  decreases) the exponent  $\alpha$  (=p/3) increases (see Fig. 8).

The above discussion leads to the conclusion that electron-phonon interactions may be responsible for the temperature dependence of  $\sigma$  at higher temperatures. At the same time one wonders if it is justifiable to extend to such high temperatures the theories that were developed for explaining small quantum corrections to  $\sigma$  at low temperatures. Though the explanation given by us seems to work, an element of doubt remains.

#### D. The metal-insulator transition

The continuity of behavior of  $\sigma(T)$  just above and below the transition and the fact that we can get  $\sigma(T=0)/\sigma_{Mott}\approx 0.01$  strongly suggest that we have a continuous transition and an absence of a minimum metallic conductivity. In our opinion the  $\sigma_{Mott}$  signifies the conductivity where classical Boltzmann transport breaks down and the quantum corrections become important. In these materials, the temperature dependence of  $\sigma$  is governed by the interaction effects over the whole temperature range. The breakdown of screening near the *M-I* transition occurs because near the Anderson transition the screening is effective only in length scales larger than  $\xi$ .<sup>15</sup>

In the insulating side of the transition we find that the hopping behavior is of the correlated type, which suggests that a Coulomb gap opens up in the single-particle density of states at the Fermi level. The M-I transition in this material is thus strongly influenced by the correlation effects.

It should be pointed out that this investigation may be the most comprehensive study of the conductivities of these materials over a large temperature range and close to the metal-insulator transition.

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- <sup>1</sup>The Metallic and Nonmetallic States of Matter, edited by P. P. Edwards and C. N. R. Rao (Taylor and Francis, London, 1985).
- <sup>2</sup>E. Abrahams, P. W. Anderson, D. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. **43**, 718 (1979).
- <sup>3</sup>M. A. Dubson and D. Holcomb, Phys. Rev. B 32, 1955 (1985).
- <sup>4</sup>Z. Ovadyahu, J. Phys. C 19, 5187 (1986).
- <sup>5</sup>T. F. Rosenbaum and S. A. Carter, J. Solid State Chem. 88, 941 (1990).
- <sup>6</sup>K. P. Rajeev, G. V. Shivashankar, and A. K. Raychaudhuri, Solid State Commun. **79**, 591 (1991).
- <sup>7</sup>J. P. Dourmerc, M. Pouchard, and P. Hagenmuller, in *The Metallic and Nonmetallic States of Matter* (Ref. 1), p. 287.
- <sup>8</sup>A. S. Ribnick, B. Post, and E. Banks, in *Non Stoichiometric Compounds*, edited by R. F. Gould, Advances in Chemistry Series, Vol. 39 (American Chemical Society, Washington, D.C., 1963), p. 246.
- <sup>9</sup>P. A. Lightsey, Phys. Rev. B 8, 3586 (1973).
- <sup>10</sup>J. P. Dourmerc, P. Dordor, E. Maquestaut, M. Pouchard, and

- P. Hagenmuller, Philos. Mag. 42, 487 (1980).
- <sup>11</sup>L. J. van der Pauw, Philips Research Reports 13, 1 (1958).
- <sup>12</sup>R. W. Cochrane and J. O. Strom-Olsen, Phys. Rev., B 29, 1080 (1984).
- <sup>13</sup>G. Deutscher, Physica B+C 109&110B, 1629 (1982).
- <sup>14</sup>B. I. Altshuler and A. G. Aronov, Pis'ma Zh. Eksp. Teor. Fiz.
  **37**, 349 (1983) [JETP Lett. **37**, 410 (1983)].
- <sup>15</sup>P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. 57, 287 (1985).
- <sup>16</sup>Y. Imry, J. Appl. Phys. **52**, 1817 (1981).
- <sup>17</sup>M. C. Maiepaard, M. Pepper, R. Newbury, and G. Hill, Phys. Rev. Lett. 61, 369 (1988).
- <sup>18</sup>F. C. Zumsteg, Phys. Rev. B **14**, 1406 (1976).
- <sup>19</sup>K. Kobayashi, Solid State Commun. 32, 1174 (1979).
- <sup>20</sup>A. Schmid, Z. Phys. **259**, 421 (1973); J. Ramer and A. Schmid, Phys. Rev. B **34**, 1352 (1986).
- <sup>21</sup>N. F. Mott, J. Noncryst. Solids 1, 1 (1968).
- <sup>22</sup>A. L. Efros and B. I. Shklovskii, in *Electron-electron Interac*tions in Disordered Systems, edited by A. I. Efros and M. Pollack (North-Holland, Amsterdam, 1985), p. 409.